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The Effect of Two Sock Fabrics on Physiological Parameters Associated with Blister Incidence: A Laboratory Study

CORNELIS PETER BOGERD, IVO RECHSTEINER, BENNO WÜST, RENÉ M. ROSSI* and PAUL A. BRÜHWILER

Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Protection and Physiology, 9011 St Gallen, Switzerland

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The goal of the present study was to investigate physiological effects, mainly at the level of the foot, of two sock fabrics with distinct moisture properties. Twelve participants wore two different socks, one on each foot. The following two sock types were used: PP: 99.6% polypropylene and 0.4% elastane and BLEND: 50% Merino wool, 33% polypropylene, and 17% polyamide. The participants walked three times on a treadmill at 5 km h^{-1}, with no gradient for the first and third phase and a 10% upward inclination for the second walking phase. The microclimate temperature between the boot and foot was measured during walking. Preceding and following the walking phases, additional measurements were carried out at the level of the foot, i.e. skin temperature and skin hydration on three locations and skin friction between the posterior surface of the calcaneus and a glass plate. In addition, the moisture absorption of boots and socks was determined. Differences between the sock fabrics were found for weight gain and microclimate temperature: (i) PP tended to hold less water compared to BLEND, (ii) the boot's microclimate temperature resulted in larger values for BLEND measured at the dorsal surface at the level of the third metatarsal, and (iii) warmer microclimates of the boot were measured for PP compared to BLEND at the distal anterior end of the tibia. The established differences in moisture behavior of both socks did not result in detectable differences in parameters measured on the skin of the foot.

Keywords: blister; footwear; friction; marching; polypropylene; skin hydration; sock; wool

INTRODUCTION

Friction blisters on the feet are among the most commonly occurring injuries among infantry soldiers (Knapik *et al.*, 1992; Reynolds *et al.*, 1999). Blister incidence was 45 ± 6% for 15 soldiers after a 20-km march (Knapik *et al.*, 1997), if a condition is excluded, during which carrying a 61 kg classic backpack resulting in an 80% blister incidence. A combination of passive and active surveillance resulted in incidences ranging from 8 to 17% caused by one marching day (Knapik *et al.*, 1992; Reynolds *et al.*, 1999). Blisters not only cause discomfort, they can also develop into more serious disorders such as cellulitis or sepsis if not treated properly (Akers and Sulzberger, 1972; Hoeffler, 1975). In fact, blisters result in off-duty time of an average length of 2 days for 2–10% of soldiers (Knapik *et al.*, 1992, 1996). In addition, Van Tiggelen *et al.* (2009) have suggested that blister-induced discomfort causes changes in gait patterns, in an attempt to reduce this discomfort, which can lead to overuse injuries, e.g. at the knee and ankle.

Friction blisters are caused by friction between the skin and its surroundings, in the form of shear forces (Naylor, 1955; Sulzberger *et al.*, 1966), which are

*Author to whom correspondence should be addressed.
Tel: +41 71 274 77 65; fax: +41 71 274 77;
e-mail: rene.rossi@empa.ch

usually expressed as a coefficient of friction (COF). It is well established that the COF increases with increasing hydration levels of the skin (Sulzberger *et al.*, 1966; Nacht *et al.*, 1981; Elsner *et al.*, 1990; Kenins, 1994; Gerhardt *et al.*, 2008) as well as with increased moisture levels of textiles (Gwosdow *et al.*, 1986). In fact, the COF can be increased by a factor of ≥ 2 under moisturized conditions (Sulzberger *et al.*, 1966; Nacht *et al.*, 1981; Gwosdow *et al.*, 1986; Gerhardt *et al.*, 2008). Average sweating rates per foot are substantial (Taylor *et al.*, 2006) and are likely to result in moisture build-up inside the foot–sock–boot system. It is therefore not surprising that reducing the sweat rate by $\sim$50% using antiperspirants reduced blister incidence in soldiers during a cross-country hike (Darrigrand *et al.*, 1992; Knapik *et al.*, 1998). One study reported that the antiperspirant coincided with skin irritation for most soldiers (Knapik *et al.*, 1998) and therewith proved that the employed antiperspirant was no functional remedy against blisters.

Different fabrics manage moisture differently (e.g. Rossi *et al.*, unpublished data) and might therefore contribute to a reduced blister incidence. Ideally, a sock keeps the skin dry as well as a layer of the fabric in direct contact with the skin. Therefore, several studies have investigated the effect of blister incidence as a function of sock fabric. Herring and Richie (1990) found that acrylic socks resulted in fewer blisters compared to cotton socks. They followed 35 long distance runners who registered blisters following 5–10 training runs and suggested that at least part of the results could be explained by the higher resistance of cotton compared to acrylic for transporting moisture. Two other studies followed large numbers ($n > 180$) of military recruits during periods of 6 weeks (Van Tiggelen *et al.*, 2009) or 12 weeks (Knapik *et al.*, 1996). Consistent between these two studies is that reduced blister incidence was found for socks (i) defined as thicker than typical army socks and (ii) not having cotton or wool in direct contact with the skin (Table 1). However, these studies do not allow for differentiating between sock thickness and sock fabrics with regards to blister incidence. In addition, the studies on blister incidence and sock fabric did not characterize the moisture transport behavior in the utilized fabrics.

Moisture behavior in porous materials such as textiles has been characterized using X-ray radiography and tomography (Burlion *et al.*, 2006; Roels and Carmeliet, 2006; Weder *et al.*, 2006; Keiser et al., 2010). Recently, Rossi *et al.* (unpublished data) employed this method for characterizing the moisture behavior characteristics of sock fabrics. They found that, among a larger number of fabrics, polypropylene and a wool/polyamide blend were the fabrics most different from one another. Differences between these polypropylene and wool/polyamide fabrics as indicated by the tomography measurements were (i) wool/polyamide absorbed more moisture and (ii) polypropylene stored less moisture close to the skin, especially <81 kPa pressure. The latter is likely to have a direct beneficial effect on skin–sock friction and is in line with at least part of the rationale of previous studies on the effect of sock fabrics on blister incidence (Herring and Richie, 1990; Knapik *et al.*, 1996; Van Tiggelen *et al.*, 2009).

The goal of the present study was to evaluate two sock fabrics similar to the polypropylene and wool/

Table 1. Summary of the two studies evaluating sock fabric on blister incidence in soldiers

Knapik *et al.* (1996)		Van Tiggelen *et al.* (2009)	
Sock samples	*n*	Sock samples	*n*
Combination 1 (extra thick)	91	Experimental sock (extra thick)	65
At skin: PE[a]		88% PE, 11% PA, and 1% EL	
Away from skin: 50% WO and 50% PP			
Combination 2	106[b]	Combination 1	59[c]
At skin: PE[a]		At Skin: 45% PE, 45% viscose, 8% PA, and 2% EL	
Away from skin: 50% WO, 30% CO, and 20% nylon		Away from skin: 40% CO, 40% WO, 18% PA, and 2% EL	
Standard	160[b]	Standard	65[c]
50% WO, 30% CO, and 20% nylon		70% WO and 30% PA	

CO, cotton; EL, elastane; PA, Polyamide; PE, polyester; PP, polypropylene; WO, wool.
[a]This sock is not further specified.
[b]Significantly higher blister occurance compared to combination 1.
[c]Significantly higher blister occurance compared to the experimental sock.

polyamide blends with distinctly different moisture transport behavior as characterized elsewhere (Rossi *et al.*, unpublished data). Physiological parameters were measured at the level of the whole body as well as the skin of the foot. In addition, sweat absorption of the socks and boots was assessed. Other than the fabric, the socks used in the present study were kept as similar as possible. Under controlled laboratory conditions, participants walked on a treadmill at two different intensities, aimed at causing distinct sweat rates of the foot.

METHODS

Participants

Twelve healthy male military recruits participated in the present study. The average anthropometrical characteristics of the participants were (mean ± standard deviation): age 19.9 ± 0.7 years, weight 72.5 ± 8.7 kg, height 176 ± 8 cm, and European boot size 43 ± 1. The participants wore standard marching clothing for neutral and warm conditions, referred to as ensemble C (or CNK 420) in the Swiss Army. In brief, this ensemble consisted of underwear (100% polyester), a long-sleeved shirt (cotton/polyester blend), long pants (cotton/polyester blend), a backpack (10.8 kg), a rifle (4.7 kg), and waist packs (3.9 kg). The total weight of the ensemble was of the order of 21 kg. All participants visited the laboratory once, starting either at 7:30 or at 13:00. Finally, all participants wore army boots with an integrated GORE-TEX membrane (KS Leight GTX; AKU, Montebelluna, Italy) in their corresponding size. The study was approved by the Ethics Committee of St Gallen, Switzerland. All sensors and measuring devices were calibrated according to the instructions of the manufacturer.

Intervention

The sock fabrics of interest were polypropylene (PP: 99.6% polypropylene and 0.4% elastane) and a wool blend (BLEND: 50% Merino wool, 33% polypropylene, and 17% polyamide). BLEND was changed by the manufacturer from the wool/polyamide blend characterized for moisture transport by Rossi *et al.* (unpublished data), in order to improve the similarity to polypropylene socks in terms of fit and shape. For each fabric, socks were produced (Jacob Rohner AG, Balgach, Switzerland). Besides the material, the two sock types were as identical as possible. The manufacturer was instructed to keep the shape and fit of the sock types constant. Three different sizes were constructed: 39–41, 41–42, and 43–46, according to the European sizing system. The participants wore one of each type on a given foot, either PP left and BLEND right or vice versa; this order was balanced over the participants. Finally, the socks were washed once before use, according to ISO6330 (2000), either machine washed using the defined program for PP or a programmed hand wash for BLEND.

Protocol

After the study was explained to the participant and all his questions were answered to his satisfaction, a consent form was signed. Any hairs were shaven from skin sites on the foot, which could affect the measurements. His body weight and body height were then assessed, and consecutively, skin temperature sensors and a heart rate (HR) monitor were installed. During this period, the participants wore sport slippers without socks, for a period of ~20 min. Finally, the participants underwent three walking phases of 30 min. During these phases, the participants walked with a speed of 5 km h^{-1} on a treadmill (PPS 70 L; Woodway, Weil am Rhein, Germany), during the first and last phases without inclination and during the second phase with a 10% upward inclination. All walking phases took place in a climate chamber with an ambient temperature (T_a) of 17.1 ± 1.3°C and relative humidity (RH) of 53 ± 5%. Each walking phase was preceded and followed by a measuring phase. These measuring phases took place in a second climate chamber stabilized at T_a = 25.5 ± 0.2°C and RH = 52 ± 1%. The participants were transported in a wheelchair between both chambers, to prevent any effect of walking between the chambers on the measurements, the trip taking at most 60 s. Before multiple measurements were performed in the measuring phase, the boots and socks were removed from the participants by the experimenters.

Dependent variables

Walking phase. HR and average skin temperature ($T_{sk\text{-}body}$) were measured in order to indicate any differences between the walking phases. HR was measured using a standard watch (810i; Polar, Kempele, Finland) and chest belt (T31; Polar), with a sample rate of 5 s. $T_{sk\text{-}body}$ was measured on four locations according to Ramanathan (1964), on (i) the left chest, (ii) left shoulder, (iii) right thigh, and (iv) the right shin. Every 10 s, the temperature reading from each thermistor (T3; MSR Electronics GmbH, Henggart, Switzerland) was stored on a data logger (MSR12; MSR Electronics GmbH). Finally, just before finishing a walking phases, the participants were asked to rate their whole body temperature perception on a nine point scale (−4: very cold, to 0: neutral, to 4: very hot) (ISO10551, 2001).

Microclimate temperature was measured between the boot and sock at five different locations (HUM; MSR Electronics GmbH). These locations are given in Fig. 1 and were (i) medial plantar from the medial cuneiform (M1), (ii) distal from the phalanges (M2), (iii) the distal tip of lateral malleolus (M3), (iv) the dorsal surface at the level of the third metatarsal (M4), and (v) the distal anterior end of tibia (M5). The sensors were installed by drilling holes through the boots and were secured using glue, tape, and/or needle and thread. All holes were carefully closed with putty in order to prevent air exchange between the microclimate of the boots and the ambient environment. All five sensors for one boot were connected to a data logger (MSR12; MSR Electronics GmbH) and their values were stored every 10 s.

Measuring phase. After the boots and socks were removed from the participant, they were stored in separate plastic bags and subsequently separately weighed on a scale (SB16001; Mettler Toledo, Im Langacher, Switzerland). The dry weight was also registered just before the participants donned the boots and socks.

Skin temperature of the foot ($T_{\text{sk-foot}}$) was measured using an infrared thermometer (Minisight Plus; Optris, Berlin, Germany). From each of three sites, an average signal was obtained from a 2-s period. The following sites were evaluated: (i) the plantar surface of the distal phalanx of the first digit (sole of great toe), (ii) the posterior surface of the calcaneus (backside of heel), and (iii) the dorsal surface of the third metatarsal (upper side of the center of the foot). These sites were measured on the left and right foot, respectively. Skin hydration was measured on the same foot sites as $T_{\text{sk-foot}}$, using a corneometer (CM 825; Courage & Khazaka, Cologne, Germany). Three measurements were made from each site after fresh placements of the probe; the average value was used for statistical analysis.

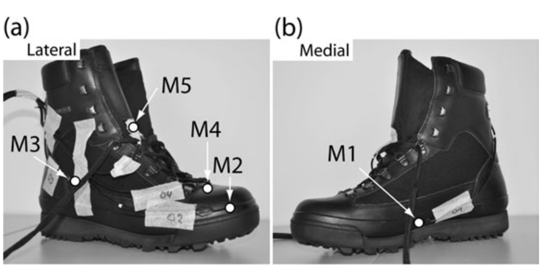

Fig. 1. The boots with the location of the sensors indicated, viewed from: (a) lateral and (b) medial. The sensors were installed between the boot and the sock and the temperature was measured; additional details are given in the text.

Skin friction was measured by moving the heel over a glass plate attached to force transducers (Fig. 2). The experimenter moved the (nude) posterior surface of the calcaneus over the glass plate from left to right and back; seven to eight such cycles were made consecutively during 60 s, first for the left foot and then for the right foot. The experimenter was trained in keeping the speed of movement and the normal force as constant as possible. A glass plate was chosen as friction partner since, in contrast to fabrics, its properties change little between measurements, and it is easy to clean using ethanol. The glass plate used (Matt 14; Fällander Glas, Zürich, Switzerland) was slightly rough since it is known that skin friction with such glass plate as reference partner increases with increasing wetness (Derler *et al.* 2009); fabrics typically show a qualitatively similar behavior. The triaxial quartz force plate (Model 9254; Kistler, Winterthur, Switzerland) was connected to amplifiers (Type 5011B; Kistler) and a data acquisition board (Model DAS16/16; Measurement Computing, Norton, VA, USA). Finally, Dynoware software (Type 2825A-02, version 2.4.1.5; Kistler) was used to record the forces with a sampling rate of 125 Hz.

Data processing and statistics

Before analysis, microclimate temperature was expressed for each subject by averaging the last 10 min of each walking phase. Weight of socks and boots was expressed as gain or loss over each walking phase. This was accomplished by subtracting

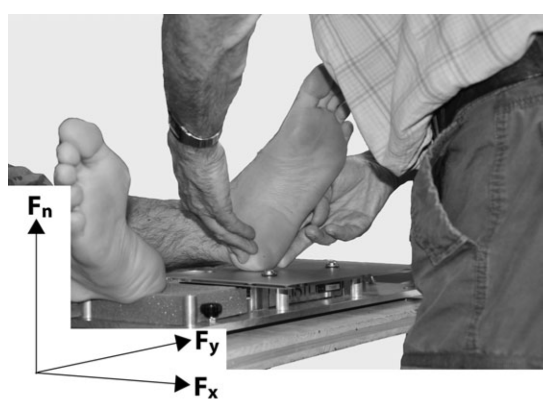

Fig. 2. A skin friction measurement carried out by an experimenter, the axis along which forces were measured are also given.

the weight measured just before the corresponding walking phase by the weight measured right after that walking phase. Data obtained from skin friction assessment were processed as follows: three forces were measured in the direction along the axes (Fig. 2): (i) the normal force (F_n), perpendicular to the force plate, (ii) F_x, along the longitudinal axis of the body of the participant, and (iii) F_y, in the direction of movement of the foot. In order to calculate the COF, first the shear (frictional) force (F_s) was calculated using $F_s = \left(F_x^2 + F_y^2\right)^{1/2}$. Consecutively, the COF could be calculated as COF $= F_s/F_n$. Each movement was separately analyzed in Matlab R2008a. Because there were strong fluctuations in the data, for the present analysis, it was decided to require a minimum period of 0.8 s (100 data points) in which the standard deviation was at most 0.015 N (~1.5% of the signal). If such a period was found, the average over this period was used for analysis. These requirements were not met in 7 of 96 cases, resulting in incomplete datasets for four participants.

A two by three (fabrics by phases) repeated measures analysis of variance for within-participant effects were used for the statistical analysis of most datasets. A Bonferroni-corrected *t*-test was used as *post hoc* comparison if the level for statistical significance was reached ($P < 0.05$). Whole body temperature perception was analyzed using a Friedman test with a Bonferroni-corrected Wilcoxon test for *post hoc* comparison. A non-parametric test was selected because the perception data were not normally distributed as indicated by a Shapiro–Wilk test, in contrast to the other parameters analyzed in the present study. All tests were carried out using SPSS 14.0 for Windows.

RESULTS

Walking phase

The average HR in the walking phases was 115 ± 13 beats min^{-1}, 150 ± 13 beats min^{-1}, and 115 ± 11 beats min^{-1}, for Phases 1, 2, and 3, respectively. HR during walking Phase 2 was significantly higher compared to the other two walking phases ($P < 0.001$). This shows that the walking intensity was higher during Phase 2. $T_{\text{sk-body}}$ during the three phases was 34.1 ± 0.5°C, 34.2 ± 1.0°C, and 32.2 ± 1.3°C, respectively. $T_{\text{sk-body}}$ was significantly lower during Phase 3 ($P < 0.01$) compared to both earlier walking phases. This might be explained by increased sweat accumulation in the clothing during walking Phase 2, which caused an increased evaporative cooling in walking Phase 3. Finally, whole body temperature perception was 1.4 ± 0.7 (corresponding to slightly warm), 2.5 ± 0.8 (corresponding to hot), and 0.6 ± 0.5 (corresponding to slightly warm), for walking Phases 1 through 3, respectively. Phase 2 was rated warmer compared to Phases 1 and 3 ($P < 0.05$); the latter two were indistinguishable from each other. As expected, these parameters did not show a difference between sock types; however, they confirm the higher physical intensity level of walking Phase 2.

The boot's microclimate temperature showed an intervention effect as well as a time effect for M4 ($P < 0.05$ and $P < 0.001$, respectively) and M5 ($P < 0.01$ and $P < 0.01$, respectively). Moreover, BLEND resulted in higher temperatures compared to PP for M4. The temperature differences for M4 were 1.7 ± 1.5°C, 1.2 ± 1.8°C, and 1.2 ± 2.0°C, for each walking phase, respectively. Whereas PP resulted in higher temperatures compared to BLEND for M5 of 2.3 ± 2.0°C, 2.6 ± 1.7°C, and 1.4 ± 1.9°C, respectively. The time effect indicated higher temperatures for Phase 2 compared to both other phases for M4; for M5, higher temperatures were found for Phase 2 compared to Phase 1 only. Locations M1 through M3 did not shown any significant effects. Finally, the absolute temperatures as well as the interaction effects are given in Table 2.

Measuring phase

The moisture absorbed by the boots and socks is expressed as the change over a given walking phase (Fig. 3). These absorption rates indicate a general intervention effect ($P < 0.01$), indicating that PP absorbed less moisture than BLEND. In turn, the boot absorbed more moisture in combination with PP. However, the combined weight differences did not indicate a general intervention effect, although interaction effects ($P < 0.01$) were found as shown in Fig. 3. The absolute weight of the boots and socks is given in the supplementary material in the online edition (Supplementary Data are available at *Annals of Occupational Hygiene* online).

For $T_{\text{sk-foot}}$, no intervention effects were found among the three skin locations. Whereas one meaningful interaction effect was found indicating an increased $T_{\text{sk-foot}}$ for BLEND during measuring Phase 2 at the dorsal surface of the third metatarsal ($P < 0.01$). The temperature difference here between PP and BLEND was 0.3 ± 0.4°C. However, all locations indicated a time effect ($P < 0.001$), revealing lower $T_{\text{sk-foot}}$ during measuring Phase 1 compared to the other measuring phases with 2.5 ± 2.6°C, 3.0 ± 0.9°C, and 1.1 ± 0.9°C for the plantar surface of

Table 2. Absolute microclimate temperature (°C) averaged over the last 10 min of exercise. Measurements took place between the boots and socks, for the five locations given in Fig. 1, and each walking phase as indicated

Phase	1		2		3	
Fabric	PP	BLEND	PP	BLEND	PP	BLEND
Location						
M1	30.5 ± 1.3	29.9 ± 1.7	30.3 ± 1.1	30.0 ± 1.4	30.1 ± 1.5	29.5 ± 1.5
M2	27.3 ± 1.5	27.0 ± 1.3	27.5 ± 1.6	27.3 ± 0.9	27.2 ± 1.7	27.2 ± 1.4
M3	30.3 ± 1.5	30.1 ± 1.4	30.6 ± 1.1	30.1 ± 1.9	30.1 ± 1.2	29.9 ± 1.7
M4[a]	30.1 ± 0.9	31.8 ± 1.4[b]	31.1 ± 1.5	32.3 ± 1.2	30.1 ± 1.4	31.3 ± 1.7
M5[a]	32.8 ± 1.5	30.5 ± 1.1[b]	33.6 ± 1.2	31.0 ± 1.4[b]	32.4 ± 1.2	31.0 ± 1.0[b]

[a]Intervention effect, $P < 0.05$.
[b]Interaction effect (fabric by phase), $P < 0.05$.

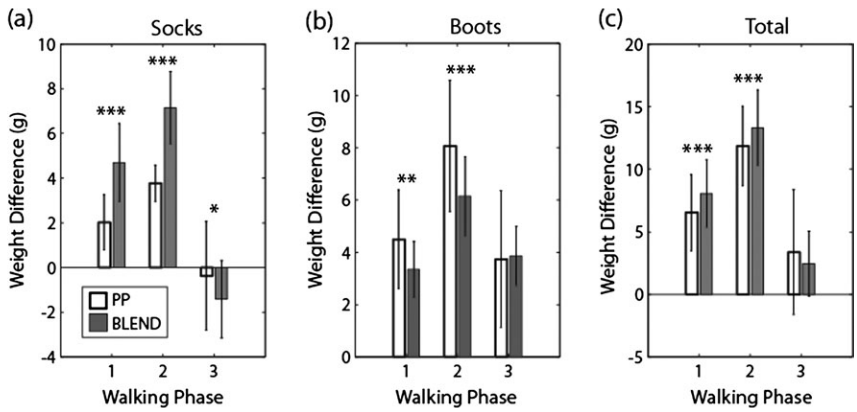

Fig. 3. Weight difference over each walking phase for (a) socks, (b) boots, and (c) both combined (total), for the sock fabrics as indicated. The weight difference quantifies the moisture absorbed or lost over a walking phase. An error bar represents 1 SD. Significant differences between sock fabrics are indicated as: $*P < 0.05$, $**P < 0.01$, $***P < 0.001$.

the distal phalanx of the first digit, posterior surface of the calcaneus, and the dorsal surface of the third metatarsal, respectively.

Results for skin hydration were qualitatively similar to $T_{\text{sk-foot}}$. That is, no intervention or interaction effects were found. However, a time effect was present, indicating lower values (drier skin) for measuring Phase 1 compared to the other measuring phases ($P < 0.001$). The COF from eight participants could be analyzed because of the missing cases, as explained under Data analysis and statistics. Figure 4 gives all analyzed COF. Similar to $T_{\text{sk-foot}}$ and skin hydration, no intervention or interaction effects were found for this parameter, although a time effect indicated a difference for the COF between the first and the second measuring phase ($P < 0.05$).

DISCUSSION

The present results indicate the different moisture transport behavior of the two sock fabrics, as reflected by the moisture absorbed in socks and boots. The differences in moisture absorbed by the socks and boots are in line with recent measurements carried out in our laboratory (Rossi *et al.*, unpublished data), as explained in the introduction. Relevant for the present results is a period of 60 min from the before-mentioned study during which 497 ± 18 g h^{-1} m^{-2} perspiration was applied, under two different static pressures, simulating the pressure range of participants standing on one foot: 0.4 kPa and 81 kPa. Among other samples, they evaluated the same polypropylene sock as used in the present study, although without elastane, as well as a wool/polyamide blend, which slightly differed from BLEND used in the present study. Despite the relatively large differences in moisture transport behavior between these fabrics, no effects were found on physiological parameters of the skin of the foot, such as $T_{\text{sk-foot}}$, hydration, and friction.

It should be noted that it is likely that during the limited time that the foot was outside of the sock

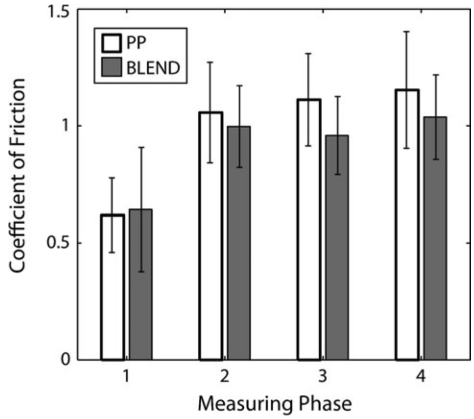

Fig. 4. COF between skin of the posterior surface of the calcaneus and a glass plate, for each measuring phase. An error bar represents 1 SD.

and boot and before measurements took place, evaporative cooling occurred. In order to quantify this, a paired analysis was carried out comparing a given location between the left and the right feet. Since the left foot was always measured ∼1 min before the right, it could reveal such cooling effect. Typical paired differences were maximally 0.1°C with a standard deviation of minimally 0.5°C, as expacted no significant difference was found. The steady state walking values for $T_{\text{sk-foot}}$ as well as hydration could therefore be slightly further away from neutral as reported here, although this effect is undetectable over a 1 min period.

The microclimate temperature does not include this uncertainty since it was measured while the boot was worn during the walking exercise. Another recent study investigated microclimate temperatures between boots and socks for runners and hikers, exercising on a treadmill in an ambient temperature and RH of 25 ± 2°C and 50 ± 5%, respectively (Bertaux *et al.*, 2010). They report a microclimate temperature combining both running and walking as 33.4 ± 1.8°C, after 20 min of exercise. Measurements were taken from locations comparible to M1 and M2 from the present study (Fig. 1); their average is reported above. The present study finds a microclimate temperature of 28.7 ± 2.0°C for these locations combined overall walking phases. The microclimate temperature difference between the two studies is substantial with 4.7°C. The ambient temperature was ∼8°C lower in the present study. Therefore, the microclimate likely reflects a reduced skin temperature due to larger heat loss from the participants in the present study. This indicates an important role for ambient temperature on boot microclimate temperature, although also clothing and boot and sock characteristics will affect heat loss. Finally, the opposite effect for M4 resulting in significantly warmer temperatures for BLEND compared to M5, which was wamer for PP, cannot be explained by the present results.

Previous studies have assessed the effect of clothing made of different fabrics on physiological parameters (Holmer, 1985; Li *et al.*, 1992; Bakkevig and Nielsen, 1995; Ha *et al.*, 1995; Kwon *et al.*, 1998; Park *et al.*, 2006, Kar *et al.*, 2007; Wickwire *et al.*, 2007; Zhou *et al.*, 2007; Guo *et al.*, 2008; Laing *et al.*, 2008; Ciesielska *et al.*, 2009). However, large methodological differences exist between these studies. Therefore, the present results cannot be compared to a generally supported hypothesis on the effect of fabric type on the physiological parameters measured in the present study. However, a clear effect has been found between measuring Phase 1 and the other measuring phases. No difference was found among measuring Phases 2 through 4. Gerhardt *et al.* (2008) evaluated the effect of skin hydration and the COF for the skin of the inner forearm. Their statistics indicated temporally undistinguishable skin hydration and COF after immersing in an isotonic sodium chloride solution for 5 min up to 30 min, although they found a difference between dry and immersed. This indicates that skin hydration and COF change noticeably after 5 min of immersion, whereas immersion >5 min up to 30 min does not cause detectible changes in these parameters. The present results suggest that a similar mechanism is valid for realistic walking conditions during which increases in skin hydration are caused by sweating instead of immersion.

It can be concluded that the COF between the skin of the foot against a glass reference partner with constant conditions was indistinguishable and independent from the sock type worn. However, under realistic walking conditions, the reference partner is a sock, under such conditions different fabrics might result in different COF. It has, for instance, been found that moisture-repelling fabrics exhibit lower COF (Elkhyat *et al.*, 2004) and that the COF increases with the increased moisture content of a fabric (Gwosdow *et al.*, 1986; Gerhardt *et al.*, 2008). However, also other construction factors of socks influence the COF (Baussan et al., 2010; Guerra and Schwartz, unpublished data). It remains an open question how the COF of the skin is affected while walking, where the sock worn is the reference.

From the total moisture absorption, the sweat rate can be approximated, if it is assumed that evaporation is negligible. The foot surface area approximates 7% of the total body surface (DuBois and DuBois, 1915; Weiner, 1945; Yu and Tu, 2009), measured from the ankle–grid downwards (Yu and Tu, 2009), hence acquiring 221 ± 88 g m^{-2} h^{-1}, 381 ± 96 g m^{-2} h^{-1}, and 88 ± 112 g m^{-2} h^{-1}, for walking Phases 1–3, respectively. Recently, two studies reported the sweat rate of the foot with a relatively high spatial resolution, while exercising in a warm environment; reporting spatially and temporally averaged sweat rates of 447 g m^{-2} h^{-1} (Taylor *et al.*, 2006) and 391 g m^{-2} h^{-1} (Fogarty *et al.*, 2007). The exercise rates of these studies are best compared to walking Phase 2 of the present study. Taking the variance of the sweat rate during Phase 2 into account, the two before-mentioned values fall within 1 SD of the sweat rate measured in Phase 2; they therefore are likely to be indistinguishable. The similarity of these sweat rates also indicates that the water loss through evaporation of the foot–sock–boot system is small. Relatively low sweat rates were observed during walking Phase 3 compared to the other walking phases. This might be explained by (i) decreased evaporation due to a larger level of sweat saturation of the sock–boot system and/or (ii) a lower overall sweat rate initiated by the lower $T_{\text{sk-body}}$ and possibly lower core temperature (not measured). Others have suggested that hidromeiosis (a decline in sweat rate during exposure to heat) could play a role after 50 min of intensive walking (Fogarty *et al.*, 2007), which could explain part of the reduced sweat rates during walking Phase 3.

CONCLUSIONS

Differences between the sock fabrics were found for weight gain and microclimate temperature: (i) the polypropylene sock (PP) tends to hold less water compared to the wool/polypropylene/polyamide blend sock (BLEND), (ii) the boot's microclimate temperature resulted in larger values for BLEND measured at the dorsal surface at the level of the third metatarsal, and (iii) warmer microclimates of the boot were measured for PP compared to BLEND at the distal anterior end of tibia. The established differences in moisture behavior of the two sock fabrics did not result in measurable differences in parameters measured on the skin of the foot, i.e. temperature, hydration, and friction. It is suggested that a surge in these parameters lasts minutes; the development thereafter is undetectable, within the conditions of 30 min of walking as for the present study.

Creating larger moisture buffers in the sock–boot system away from the skin as well as increasing the ventilation within the footwear might extend the period in which a measurable difference can be observed, in parameters measured in the present study on the level of the foot. The studies mentioned in the introduction finding an effect of sock fabric on blister incidence during multi-week military basic training not only changed the fabric but also the sock thickness as well (Knapik *et al.*, 1996; Van Tiggelen *et al.*, 2009). The lack of any difference in physiological parameters between the two fabrics suggests that sock thickness also plays an important role. However, interesting open questions remain (i) which aspects of sock thickness are beneficial, increased moisture storage, or increased friction absorption from boot to foot, or other aspects; (ii) the COF between the skin and the sock during walking; (iii) what are the perceptual (e.g. temperature and comfort) differences between the sock fabrics; and (iv) does the lack of difference between sock fabrics in the parameters measured at the level of the foot remain for multiple hours of walking? The development of a method measuring the COF between the skin and the sock worn under realistic conditions, perhaps even during walking, would help to further understand the effect of sock fabric on the COF, especially if this method is validated against blister incidence.

SUPPLEMENTARY DATA

Supplementary data can be found at http://annhyg.oxfordjournals.org/.

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